| REPORT DOCUMENTATION PAGE | | | | *Form Approved* *OMB NO. 0704-0188* |
|---|---|---|---|---|



| | | |
|---|---|---|
| 1. AGENCY USE ONLY *(Leave blank)* | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED<br>[redacted] |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>TITLE ON [redacted] | 5. FUNDING NUMBERS<br>DAAH04-96-1-0389 |
| 6. AUTHOR(S)<br>AUTHOR(S) ON [redacted] | |
| 7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)<br>University of California - Los Angeles | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>U.S. Army Research Office<br>P.O. Box 12211<br>Research Triangle Park, NC 27709-2211 | 10. SPONSORING / MONITORING AGENCY REPORT NUMBER<br>ARO 35875.119-PH-MUR |

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

| | |
|---|---|
| 12a. DISTRIBUTION / AVAILABILITY STATEMENT<br>Approved for public release; distribution unlimited. | 12 b. DISTRIBUTION CODE |

13. ABSTRACT *(Maximum 200 words)*

ABSTRACT ON [redacted]

20010618 118

| | |
|---|---|
| 14. SUBJECT TERMS | 15. NUMBER IF PAGES |
| | 16. PRICE CODE |

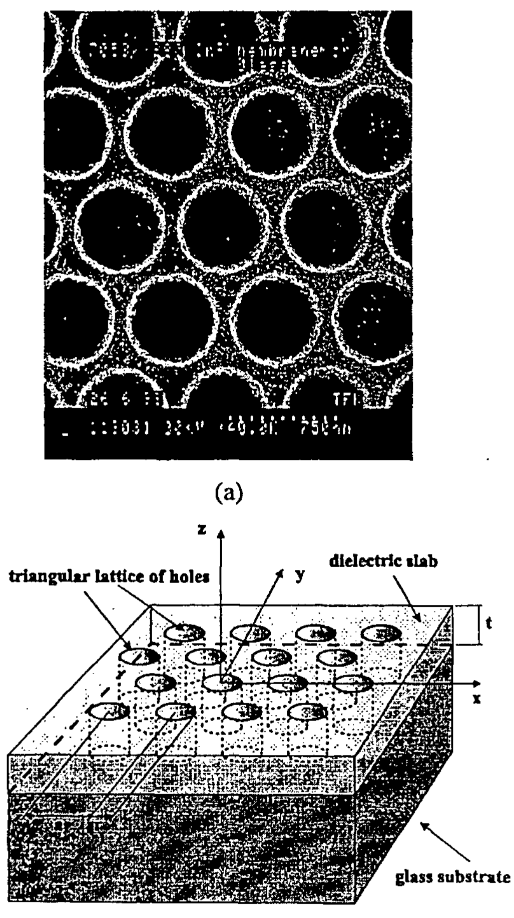
| | | | |
|---|---|---|---|
| 17. SECURITY CLASSIFICATION OR REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

# Thin Film 2-d Photonic Crystals High-Performance Light-Emitting Diodes

Misha Boroditsky[a], Rutger Vrijen[a], Thomas F. Krauss[b], Roberto Coccioli[a], Raj Bhat[c], Eli Yablonovitch[a]

[a] Electrical Engineering Department, UCLA, Los Angeles, CA 90095-1594
[b] Electrical Engineering Department, Glasgow University, Glasgow, G12 8LT, Scotland
[c] Corning, Inc., Red Bank, NJ 07701

Photonic crystals, artificially created, multi-dimensionally periodic structures are known for a forbidden electromagnetic bandgap. For that reason, they can be used to modify spontaneous emission. Initially, it was proposed to use photonic crystals to inhibit spontaneous emission[1], but they can be employed to enhance it as well, with significant implications for light-emitting diode structures. We show that thin slab 2-d photonic crystals can provide a spontaneous emission enhancement up to $F_p$=5 and an overall extraction enhancement up of 8 times. Thin-film InGaAs/InP 2-d photonic crystal at ambient temperature, but the results would apply equally to InGaN thin films for example. An MOCVD-grown $In_{0.47}Ga_{0.53}As$/InP single quantum well double hetero-structure was used for these experiments. Thin films for the photo-pumped LED's were fabricated using substrate removal, and bonded to a glass slide. A triangular array of holes is defined by electron-beam lithography, using a LEICA EBPG-5 Beamwriter. The semiconductor slab was etched through by reactive ion etching (RIE) using $SiCl_4$ at the elevated temperature of 200°C. The InP film thickness is 240nm and the InGaAs quantum well active region thickness is 60nm. Each sample had numerous triangular lattice structures spanning a photonic lattice constant range sufficient for optimization of the external efficiency. In our case of emission wavelength centered at vacuum wavelength λ=1650nm, the photonic crystal's lattice constant was made to vary from a=550nm to a=910nm. Correspondingly, the center of the photonic band gap varied from λ=1300nm to λ=1900nm. The thin-film LED photonic crystal structures are shown in Figure 1.



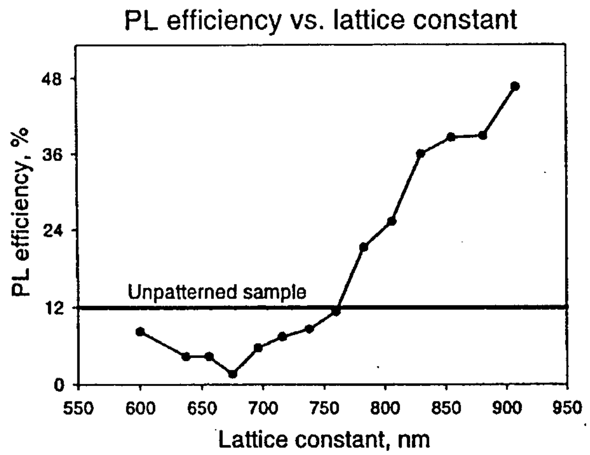

(a)

(b)

Figure 1(a)A triangular array of holes in the thin film on InGaAs/InP double hetero-structure.
(b) prospective view.

The LED emission was collected in a solid angle from normal up to 45° angle away from normal, in air. The calibrated photoluminescence signal versus photonic lattice spacing is shown in Figure 2. As can be seen from the graph, the efficiency is optimized

0-7803-5634-9/99/$10.00©1999 IEEE




Ffigure 2. Photoluminescence efficiency calibrated with respect to the reference sample, and corrected for the fractional sample absorption.

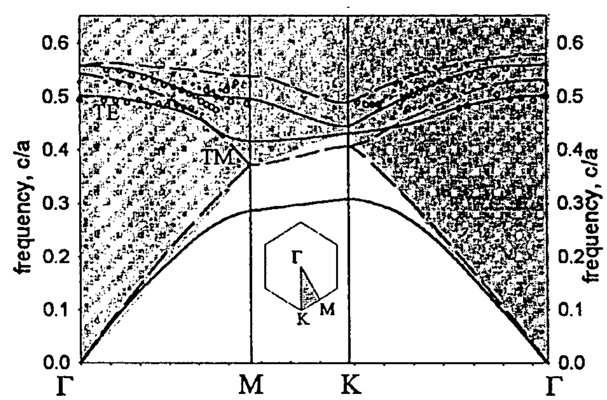



Figure 3. Theoretical (lines) and experimental (circles) bands for the thin slab photonic crystal. The modes in the shaded area are leaky.

at a photonic lattice constant ~900nm, where conduction band modes match the InGaAs emission frequency. That gives the external efficiency for that LED structure 48%.

The angular resolved spontaneous emission allows for measurements of the dispersion diagram of a photonic crystal's leaky conduction band modes, that is modes with frequencies lying above the light cone in the glass substrate. We used the evolution of spontaneous emission spectral peaks versus angle to study the band structure of the photonic crystal. The dispersion diagram (solid lines in Figure 3) is computed using the Finite Difference in Time Domain technique. Angular resolved spectra on thin film photonic crystals reveal some very sharp peaks in the spectrum compared to the reference emission linewidth of InGaAs. These are signatures of a new type of the Purcell enhancement[2], that can be realized in the spatially extended photonic bands, without a cavity.

Leaky conduction band modes bring a two-fold advantage to LED's. First, by using them, we increase dramatically the light extraction efficiency, bringing it close to 100%. Second, we can speed up the radiative recombination to make it more competitive with the non-radiative recombination on exposed surfaces. Increase in recombination rates drives faster device operation as well.

Leaky photonic crystal modes can also be used as a passive out-coupling mechanism[3]. These leaky modes are in the shaded area of Figure 3 and have measured Q between 30 and 100. The periodic structure is in effect an efficient, coherent scatterer of light from the semiconductor film. We will show that this approach allows obtaining up to 70% external efficiency LED structures.

## REFERENCES

1. E. Yablonovitch, Phys. Rev. Lett.,1987, **58** (20), pp. 2059-2062.
2. E.M. Purcell, Phys. Rev. **69**, 681(1946)
3. M. Boroditsky *et al.*, to be published in 08/23/99 issue of Appl. Phys. Lett.